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-USSR-

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EVALUATION OF THE SEISMICALLY DANGEROUS ZONES DURING EXPLOSIONS

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[Following is the translation of an article entitled "Otsenka seysmicheski opasnykh zon pri vzryvakh" (English version above) by M. A. Sadovskiy published in Trudy Seysmologicheskogo Instituta Akad. Nauk SSSR (Proceedings of the Seismological Institute of the Academy of Sciences, USSR), No. 106, Moscow, 1941, pages 64-73.]

The possibility of a destructive seismic effect caused on structures by large explosions is indisputable. However, because of the confusion caused when workers who know little about explosions attempted to evaluate the effect of explosions by means of methods used in studying the intensity of earthquakes, a clearly exaggerated concept of the seismic danger of explosions developed. Experience has shown that, because of the fear caused by seismic phenomena accompanying explosions, in many cases a significant amount of time was wasted in unfounded discussions on the possibility of the occurrence of explosions, great economic loss caused by unnecessary stoppage of electric power stations near the explosion, and other completely unnecessary consequences no less harmful to the national economy.

It is apparent that all of these harmful consequences result from the fact that workers in industry are poorly informed on the true nature of the seismic effect explosions have on buildings and structures. For this reason the elaboration of even the simplest methods of evaluating the true seismic danger involved in explosions should be recognized as a fundamentally important problem.

Great mathematical difficulties accompany a precise solution of the problem involving the effect of oscillation of the ground on buildings and constructions. For this reason a precise solution is hardly possible for each specific case involving the seismic effect of an explosion.

We will limit our problem to an elementary investigation, the goal of which will be to give a simplified picture of the mechanism involved in the destructive seismic effect of explosions based on the following well-known dynamic factors of structures:

(1) Any engineering structure is a mechanical system with a characteristic oscillation period of its own.

(2) The effect of a compelling ground oscillation on a structure is greater, the closer the period of these oscillations is to the period of the given structure.

On the basis of these conditions the oscillation of the ground must be evaluated from the point of view of the relationship between its own period and the period of the structure as well as from the point of view of absolute intensity. Therefore as our first problem we must establish the range of periods found in contemporary structures and buildings and evaluate the limits of oscillation periods in the ground during explosions. The first of these tasks is already accomplished in many works on the dynamics of structures which give the basic periods for typical structures and buildings. Periods lie in the range between 0.3 and 1.0 seconds.

Somewhat greater difficulties are met in finding the limits of oscillation periods for the ground during explosions. For the sake of clarity in the rest of this article we give here a short description of the nature of oscillations in explosions.

A typical oscillation record of an explosion is shown in Fig. 1. Two phases of oscillation stand out clearly on this seismogram, as on any other such record taken near the explosion (in the zone where the radius, $R \leq 2$ kilometers). The first of these, the primary wave, is a short-period, low-amplitude oscillation which dies out quickly. The period of this phase in various cases varies from thousandths to hundredth parts of a second. The duration is one or two complete oscillations.

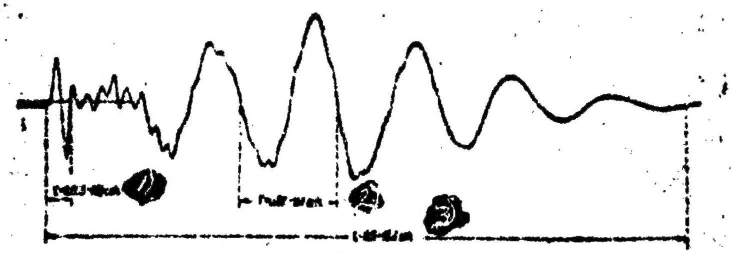


Fig. 1

(cek = seconds)

Legend: 1) t = 0.005-01.5 seconds; 2) t = 0.02-0.4 seconds; 3) t = 0.5-15.0 seconds.

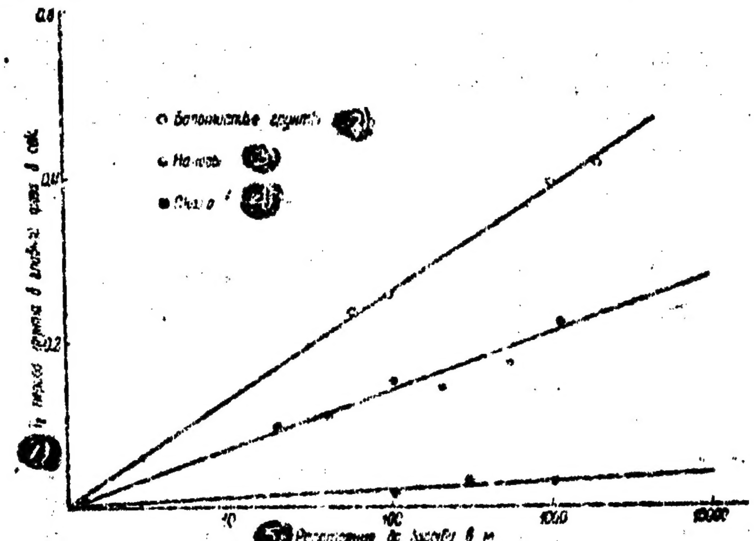


Fig. 2

Legend: 1) T_2 period of the ground in the principal phase in seconds; 2) swampy ground; 3) sediments; 4) rock; and 5) distance from the explosion in meters.

In the second phase, the oscillation grows agina. The amplitude reaches a much higher peak than the one observed in the primary phase. A definite period characterizes this phase. The magnitude does change depending on the physical and mechnical properties of the ground at the point of measurement and its distance from the explosion. When ground conditions are constant and distance is euqal the magnitude remains fairly constant. It should be noted here that the existence of a specific oscillation period for the ground in the second and main phase of oscialation has as yet received no satisfactory explanation.

One would expect a complete spectrum of periods in the oscillation of a practically unlimited mass of ground rather than a specific period characteristic for the ground since the occurrence of the latter is possible only for oscillation of a body of limited dimensions. We do not intend to go into this question. We would like to note only that one of the reasons for the occurrence of oscillations with a specific period can be the reflection of waves in a layer of earth of finite thickness. However, that may be, the existence of a dominant period in the main phase of oscillation is a fact which is constantly observed.

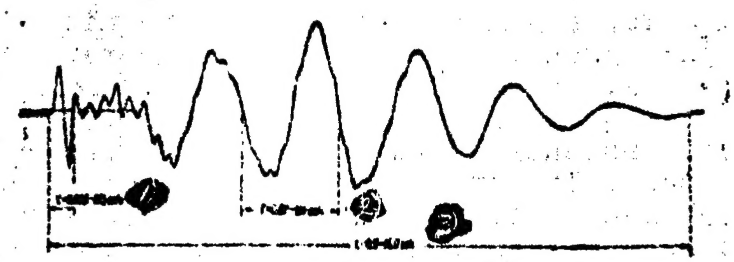
It has been mentioned supra that the period of oscillation T_2 in the main phase depends on the properties of the ground and on distance. The nature of these relationships is little known. To get some idea of the magnitude of the period T_2 in various types of ground, we may recommend the following empirical formulae in which r signifies the distance in meters:

First group $T_2 = 0.13 \lg r$ -- swamp, strongly water saturated sediments (1)

Second group $T_2 = 0.07 \lg r$ -- sediments (clays, loess, etc.)

Third group $T_2 = 0.01 \lg r$ -- rock (granites, dolomites).

The formulae listed show satisfactory results for distances between 20 and 2000 meters, as shown in Fig.2. From the formulae for T_2 it would seem that the oscillation periods for ground can have any value since they increase with distance. In this instance the problem of determining the limits of T_2 which we have proposed would be senseless. However, oscialation caused by explosions rapidly dies out with increase in distance and becomes so small at great distances that its effect on structures may be neglected. Thus, for example, only zones with a radius less than 1000 meters are seismically dangerous even for the largest explosions



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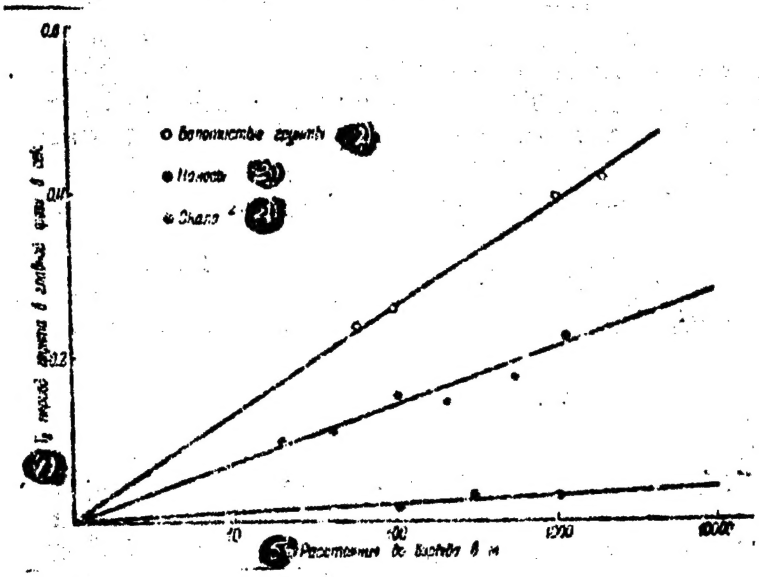

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we have produced at present (up to 500 T.). If we take 1000 meters as a limiting distance, we may calculate from the formulae above that the limiting maximum value of the period T_o for the ground will be 0.4 seconds for swamps, 0.21 for sediments, and 0.03 for rock. Considering that structures are not generally built in swamps, we may take the limiting magnitude of the oscillation period of the ground during explosions as 0.01 -- 0.3 seconds.

Some results of seismic effects of explosions obtained by the Seismological Institute of the AN (Akademiya Nauk Academy of Sciences), USSR (the work of F. A. Kirillov and M. A. Sadovskiy) should be mentioned. Instrumental observations of oscillations caused by explosions show that:

1) the amplitude A and the velocity v of oscillation are functions of the relationship $\frac{\sqrt[3]{c}}{r}$ where c is the weight of the explosive BB, r is the distance from the explosion point to the observation point;

2) the amplitude of the oscillation depends on the properties of the ground; the magnitude of the oscillation velocity may be considered as not depending on the nature of the ground at the observation point;

3) the decrease in intensity of oscillation with distance is greatest near the explosion. With increasing distance from the explosion, the decrease in intensity becomes slower. Thus, for example, an empirical expression for the velocity v of oscillation of particles of ground may be written in the form:

$$v = k \left(\frac{\sqrt[3]{c}}{r} \right) \qquad (2)$$

where ν = 1 for small $\frac{\sqrt[3]{c}}{r}$ and ν = 2 for large $\frac{\sqrt[3]{c}}{r}$;

4) comparison of seismic damage sustained during explosions with the magnitudes of amplitude, velocity, and acceleration of ground oscillations which were involved in the explosion shows that there is a direct relationship between the magnitude of oscillation velocity and damage sustained. Experience shows that damage is observed only when the velocity of the oscillation is equal to or greater than 12 -- 14 cm-sec for structures located on ground of intermediate hardness (sediments).

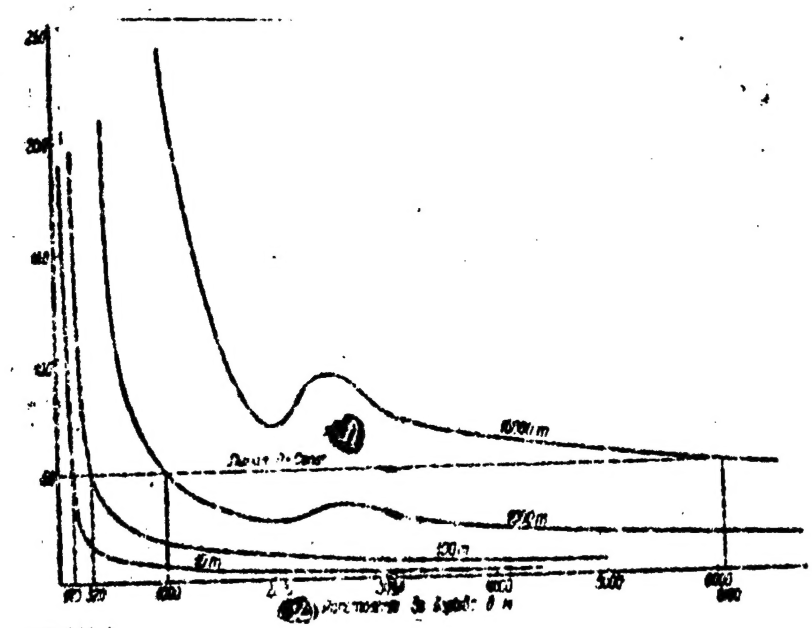

Fig. 3

Legend: 1) Line D = const.; 2) Distance to the explosion in meters.

EVALUATION OF DESTRUCTIVE SEISMIC CAPABILITIES OF EXPLOSIONS

Let us now evaluate the destructive capabilities of oscillations during explosions. For this let us make some simplifying assumptions. Thus, for example, we will consider that the foundation of the structure is firmly attachedto the ground and that the structure is a system which can only oscillate in a horizontal plane with a single oscillation period (basic period).

Destruction of the structure occurs in those cases when tensions in its various parts exceed a limit inherent in the material of which the parts

are made. The tensions will in general be greater, the greater the degree of deformation of elements of the structure. The deformation of the oscillating system will grow approximately proportionally to the square root of the potential energy of the system. We will assume that kinetic energy is completely transformed into potential energy in the oscillating structure and also that the energy transmitted by the oscillations to the structure also increases with the growth of the oscillation energy of the ground. Such proposals can allow us to make no claim of precision and are made only so that we may obtain a rough evaluation of the effect of oscillation of the ground. We must note, however, that their applicability in the cases we have examined has been confirmed to a certain degree by experience.

The relationship we mentioned above between the magnitude of the oscillation velocity of the ground and amount of destruction can indeed be regarded as evidence for the existence of a relationship between deformation of elements of a structure and the energy of oscillation of the ground (the velocity of oscillation being proportional to the square root of the energy of oscillation) and, consequently, as confirmation of the applicability of the simplifying assumptions we have made. On the basis of the assumptions made we may write the following approximate expression for a deformation d of a structure:

$$d = K \cdot \beta \cdot v \qquad (*)$$

where v is the velocity of oscillation of a particle of ground, K is the coefficient of proportionality, and β is a quantity the determination of which will be given below. Expression (*) for d dose not reflect, as can easily be seen, the position we adopted on the influence of the relationship of the period of groundoscillation T_2 to the period of oscillation of the structure T_0. We can take this into consideration if we take factor β in expression (*) as a quantity showing that the necessary oscillations depend on the relationship $\frac{T_0}{T_2}$.

Having in view only an approximate evaluation of the effect of ground oscillations, we propose that if they continue they will be sufficient to cause practically complete damping of the internal oscillation of the structure. If this is so (for large explosions this proposal may be considered acceptable) β may be taken

as the so-called "oscillation increase coefficient", the mathematical expression for which has the following form:

$$\beta = \frac{1}{\sqrt{\left(1 - \frac{T_o^2}{T_2^2}\right)^2 + \gamma^2 \frac{T_o^2}{T_2^2}}} \qquad (**)$$

In the above expression γ is a quantity depending on the damping of the oscillations peculiar to the structure.

Putting the expression for β in expression (*) and taking into account (1) and (2), we get the following expression for the deformation d:

$$d = C \cdot \frac{\left(\sqrt[3]{c}\right)}{r^{\nu}\sqrt{\left\{\left(1-\frac{T_o^2}{(a\ \lg r)^2}\right)^2\right\} \gamma^2 \frac{T_o^2}{(a\ \lg r)^2}}} \qquad (3)$$

where ν, depending on r and C has a value between one and two.

Formula (3), the right half of which is a function of the distance r and two parameters: the weight BB -- c and the period T_o of oscillations peculiar to the structure can be used in establishing the dimensions of seismically dangerous zones in explosions. Having experimental data on the limiting values of the velocity of oscillation v, and knowing the quantities T_o, γ, and r, one can find the quantity d_k corresponding to the conditions of formation of the initial destruction. By making a graph of the functions $d = F(r)$ for several given quantities T_o, c, γ, and a, we get a family of curves shown in figure 3 To find the radius R_c of seismically dangerous zones using the graph in Fig. 3 one determines the abscissa of the intersection of curves $d = F(r)$ with a straight line $d = d_k$. The values of radii R_c of seismically dangerous zones determined by the above method are given in table 1 for various weights of charges BB, varidus types of ground, and structures with various oscillation periods T_o.

TABLE 1

Radii (in meters) of Seismically Dangerous Zones in Explosions

2 T_0 сооруж. \ Вес ВВ, т 1	10	100	1000	10 000	Грунт 3
0.3 0.6 0.9	650 140 70	1170 320 190	2270 1000 400	4000 6100 1250	Слабый, насыщенный водой 4
0.3 0.6 0.9	180 70 13	350 120 75	1330 380 140	3200 1000 600	Наносы 5
0.3 0.6 0.9	— — —	30 — —	100 50 —	250 100 50	Скала 6

Legend: 1) Weight, tons; 2) T_0 of structure; 3) Type of ground; 4) Weak, water saturated; 5) sediments; 6) rock.

The value of d_k was calculated for buildings with a period of 0.3 -- 0.35 sec. Damage which occurred under conditions corresponding to the chosen value d_k were of an initial type in nature such as: the appearance of narrow cracks in brick walls and ovens, fissures in window frames, falling of plaster, etc. To illustrate the correspondence of the calculated values of R_c with actual cases we have given in table 2 some data on seismic damage during explosions taken from records of the Soyuzvzryvprom (Union explosive industry /probably abbreviation for soyuznaya vzryvatel'naya prommyshlennost'/).

As can be seen from the table, the results of evaluation of the radius of the seismically dangerous zone tie in completely with experience.

Only data for the most characteristic explosions are given in table 2. For these, observations were made either at several points or close to the border of the danger zone, R_c was also determined for many other explosions. Contradictions between experimental data and the calculated dimensions of the seismically dangerous zones were not found in a single case.

For this reason we are able to recommend the method described above to all organizations conducting explosive work for an approximate determination of the seismic danger of large explosions. The following things are necessary for practical use of this method:

1) The properties of the ground in the area where the structures and buildings are located must be known.

2) The periods of oscillation of the structures and buildings must be known.

3) Table 1 may be used to find the required radius R_c for a given weight BB by interpolation.

The amount of moisture in the ground and the presence of ground waters must be considered in evaluating the properties of the ground. Very wet ground should be considered in the first group (swampy ground). Table 3 may be used to determine the period of oscillation for structures in a general way so that complete studies of their construction are not necessary. These data are taken from the book by Syuekhiro, "Engineering seismology", and from observations of the Seismological Institute of the AN USSR.

In applying the proposed method, it must be remembered that the radius R_c of the seismically dangerous zone will undoubtedly change also depending on the durability of the structure. Thus, for example, the Radius R_c will be smaller for reinforced concrete structures than we have calculated it to be for brick buildings of medium-quality construction. However, since various elements of a structure are not of equal durability, it is better not to figure corrections for the increased durability of structures into the calculated values of R_c in order not to meet with possible cases where partial destruction of weaker construction elements occurs.

Table 2

Place and type of explosive work	Weight BB (tons)	distance meters	Damage	Radius of seismically dangerous zone	Remarks
Imanskiy mining directorate "Primorzoloto", waste	83.6	200 300 400	yes yes none	370	ground-yellow clay with pebbles Homes T_o = 0.3
Khramtsovskiy coal deposit, waste	160	400 500	yes none	520	ground-clay -- two story houses
Korkino, on waste	1860	400 600 1200	yes yes none	1700	ground-sediments clay soil. One-story stone buildings, locomotive depot. Samannyy electric substation
Krivoy Rog, "Artem" in hanging wall	25	60 100 120 190 200	yes yes yes yes none	190	ground-loess-clay-soil. One-story stone houses
Bodinskiy sulfur mine, waste	88.7	180 215 240	yes yes yes	350	ground-dry sediments one-story dining room old house

Highway Minsk-Moscow	113.3	300	none	400	dense, sandy clay. cottage of village "Yazevo"
"Pribalkhash-stroy" waste	500.8	650 1000 2000	none none none	100	ground-rock-village Kounrad. Homes
Kupyanskiy silicate org. waste	17.5	100--200	yes	200	ground-plant cover one-story houses cottages
Raychikhinskiy coal region-waste	174.5	600	yes	1360	ground-wet soil and clay. Locomotive depot
Northern part of the Urals bauxite deposit waste	48	200 740	yes none	950 260	K-ra deposit one story. Plant cover 4m. TETs, T_0=0.5 sec.
cement plant "October Victory"	94.9	50	inci-pient damage	65	ground-marls bremsberg booth T=0.04

Table 3

Characteristic periods for types of buildings

Type of building	no. of floors	basic period in sec.	source
Old brick houses	1-2	0.3-0.35	Syuekhiro, SI, AN
Brick houses	3-4	0.35-0.45	SI, AN

Wooden houses	1-2	0.4-0.5	Syuekhiro, SI,AN
Wooden houses	3-4	0.5-0.7	Syuekhiro
Reinforced concrete buildings	2	0.35-0.50	"
"	7	0.5-0.7	"
Framework steel buildings	2	0.3	"
"	5-9	0.6-1.2	"

It is obvious that the proposed method of evaluating seismic danger can not be used for structures which are in threatening technical condition. This is also the case for special structures which are significantly different in their construction from normal buildings (very tall buildings, smoke stacks, radio towers, wind measuring apparatus, etc.) Decisions on the permissibility of explosive work near such structures should be cased on results of careful mathematical analysis.

CONCLUSION

The simplified discussion of the mechanism of destructive seismic effects of explosions given above allows us to explain small damage observed during explosions in comparison with natural earthquakes. In the great majority of large explosions the value of $\frac{T_c}{T_2}$, the period of the structure T_c to the oscillation period of the ground T_2 is never less than 2 (in zone of intense oscillation), In earthquakes the value of this ratio usually lies in the range 1-03.

In evaluating the magnitude of the oscillation growth coefficient β corresponding to the values of the ratio $\frac{T_c}{T_2}$ for explosions and earthquakes, it is not difficult to notice (Fig. 4) that β for explosions lies in the range:

$$0 < \beta \leq 0.3.$$

For earthquakes the limits for β are the following:

$$1 \leq \beta \leq n$$

where n depends on the force of damping of the oscillations in the structure (where $\gamma = 0.2 - n = 5$).

Thus the values of the coefficient β for the oscillations in explosions are many times smaller than in earthquakes. It is apparent that the same relationship will also be observed for the deformation of structures during explosion and earthquake oscillation. However, this situation holds only for explosions in which the quantity EB is not too large. For very large charges the oscillations may have sufficient intensity over such distances that the value of the period of oscillation of the ground T_2 may approach the magnitude of periods characteristic for earthquakes (T_2 = 0.6-0.8 sec.). Such an instance would lead to an abrupt increase in the dimensions of the seismically dangerous zone (see table 1, "weak ground", second line, charge 10,000 tons) and to more serious damage than that normally observed.

In evaluating the destructive effect of oscillations accompanying explosions we must mention one characteristic property: damage when observed starting from somelimiting distance R_c grows only slightly in magnitude as one approaches the point of the explosion. There is as yet no complete explanation of this fact, which contradicts the simplified description of the damage mechanism presented above. The following reason may be a possible explanation for the slower increase of damage than would be expected for the growth of deformation we have given (expression (3) Fig. 2): the duration of the intensive oscillations in the main phase apparently grows with increase in distance from the explosion. Therefore our assumption that the coefficient β is identical with the oscillation growth coefficient is correct only for fairly distant zones. Close to the explosion the values of β correspond less well with the oscillation growth coefficient. Furthermore, in the zone of intensive oscillation involving high acceleration of the ground, the forces of inertia of the structure will be so great that the stability of the ground under

the foundation does not satisfy the condition we assumed of a firm connection of the structure with the ground. As a result one might expect a considerably smaller transfer of oscillation energy from the ground to the structure.

In conclusion we note that the empirical expressions

$$R_c = 1.5 \sqrt[3]{c},$$
$$R_c = 8 \sqrt[3]{c},$$
$$R_c = 20 \sqrt[3]{c}, \qquad (4)$$

we gave earlier for rock, sediments, and swampy ground (in our report to the All-Union conference on drilling and explosive work in 1939) give values which are somewhat too small for swampy ground as will be seen in table 4.

Table 4

Comparison of radii of seismically dangerous zones

Ground	Weight BB in tons	10	100	1000	10000	Remarks
Swamp	formula	430	930	2000	4300	Calculated values R_c are taken for buildings with a period T_o= 0.3 sec.
	calculation	650	1170	2270	4000	
Sediments	formula	170	370	800	1700	
	calculation	160	390	1380	3240	
Rock	formula	32	70	150	320	
	calculation	-	30	100	250	

Values of R_c also are too low for sediments when explosive charges BB of 1000 tons and greater are involved. This occurs because the formulae do not take into account resonance phenomena which cause an abrupt increase in the dimensions of the seismically dangerous zone.

In accordance with the data given in table 4 we recommend increasing the coefficient for swampy ground to 30. If this is done, expression (4) will give the maximum limit for the radius of the seismically dangerous zones for all possible cases involving explosions up to 1 000 tons BB.

March 1940

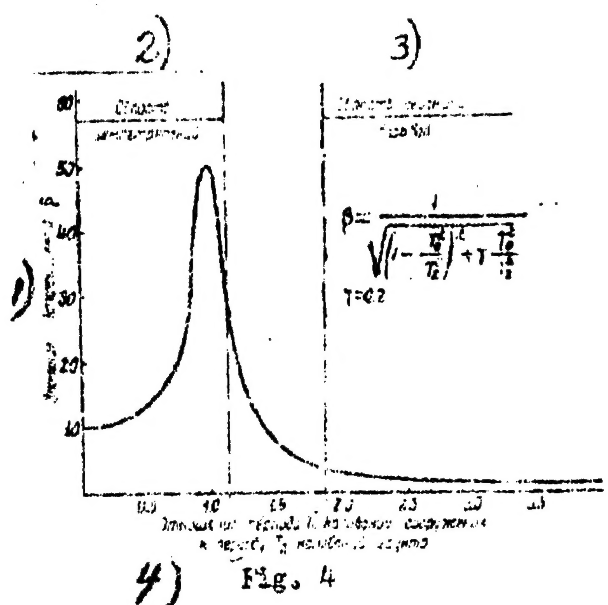

Fig. 4

Legend: 1) Value of coefficient ß; 2) earthquake zone; 3) Zone of explosive seismic effects; 4) Relationship of the period of oscillation of a structure T_0 to the period of oscillation of the ground T_2

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